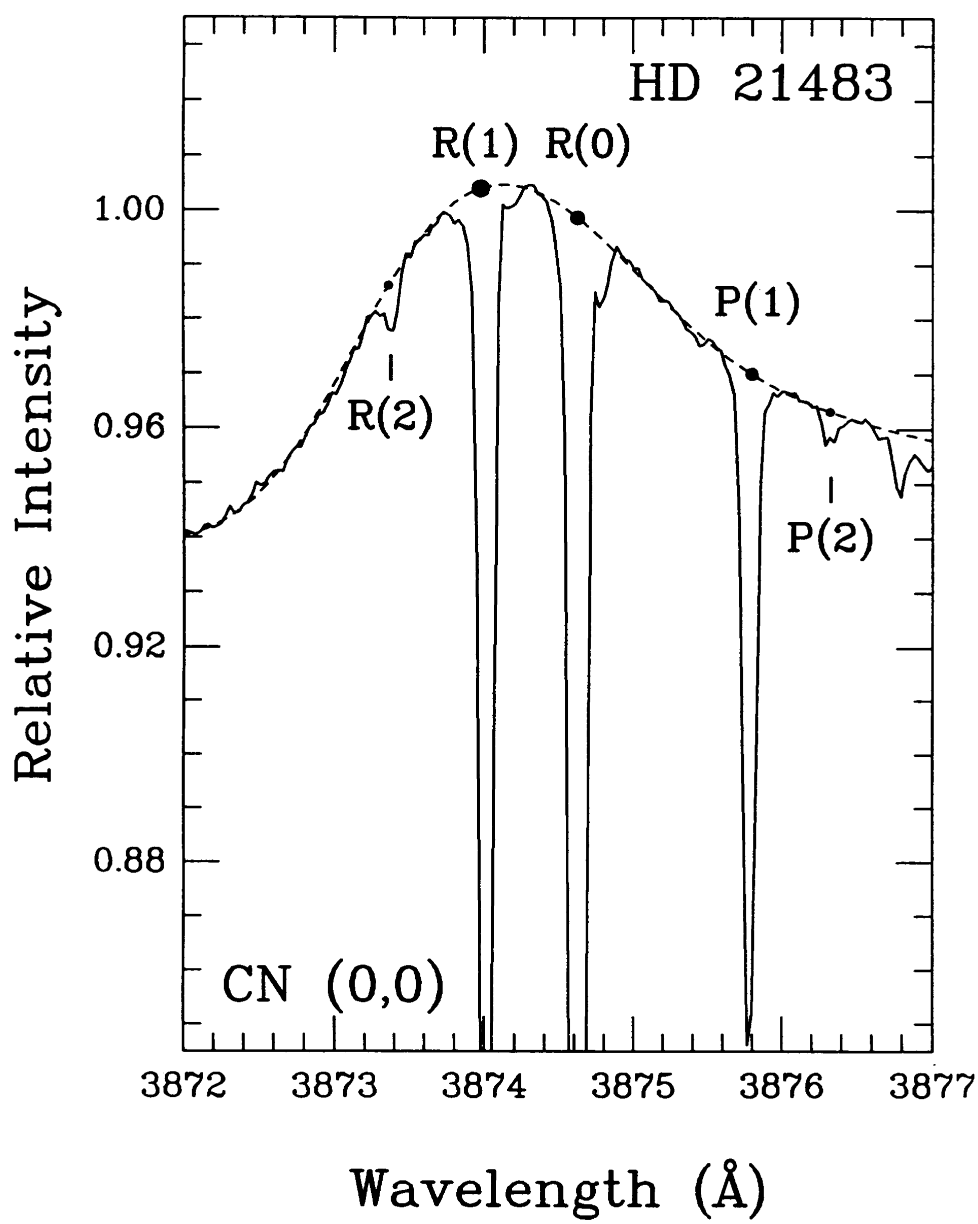
Pre-Main Sequence Evolution

Star formation begins in giant molecular clouds, with temperatures less than $\sim$ 100 K or so. In this environment, the average density of interstellar matter is $\sim$ 100 cm^{-3}, and the size of the cloud is anywhere between 10 and 100 pc. Dust is mixed in with the gas, which shields the inside of the cloud from UV radiation, keeping the temperature cold. (In fact, by measuring molecular absorption in these clouds, and assuming a Boltzmann distribution, one can obtain the temperature of the microwave background.)



The classic picture of star-formation involves a) the formation of cores in a giant molecular cloud, b) the creation of proto-stellar cores with surrounding disks, c) the breakout of stellar winds, which blow material away, and d) the termination of infall, leaving behind a star and the remnants of a disk.

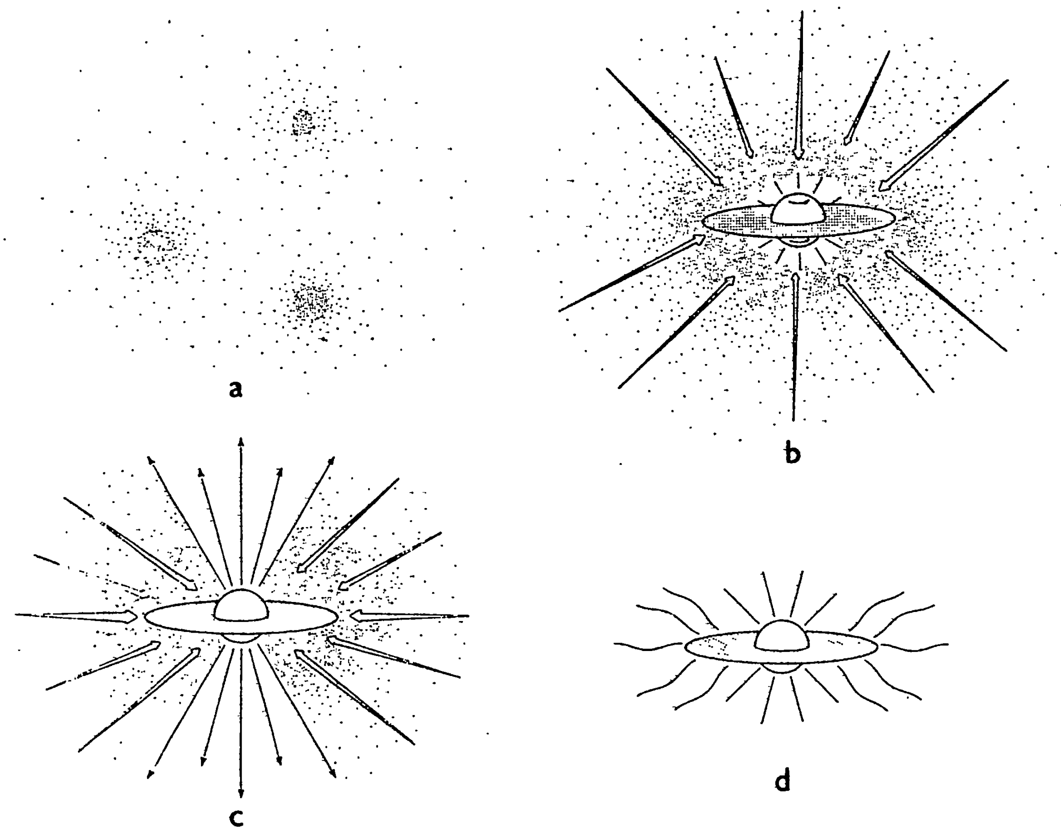


Figure 7 The four stages of star formation. (*a*) Cores form within molecular clouds as magnetic and turbulent support is lost through ambipolar diffusion. (*b*) A protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (*c*) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (*d*) The infall terminates, revealing a newly formed star with a circumstellar disk.

The Jeans Criteria

Before considering the collapse of a proto-stellar cloud, first recall the two principal results from our Virial theorem analysis: that for a stable star, thermal energy is balanced by gravitational energy, by

$$3(\gamma - 1)E_i + E_{\rm grav} = 0 \tag{10.1.8}$$

and that the total energy of a star is given by the thermal plus gravitational energy. In virial equilibrium, this is

$$W = -\frac{E_{\rm grav}}{3(\gamma - 1)} + E_{\rm grav} = \frac{3\gamma - 4}{3\gamma - 3} E_{\rm grav} \tag{10.1.9}$$

where, for a simple monotonic ideal gas, $\gamma = 5/3$, and (10.1.8) reduces to $2E_i + E_{\rm grav} = 0$. Note that if $\gamma < 4/3$, the total energy is negative, and the system must collapse.

Now consider the collapse of a gas cloud. Simply put, a cloud will collapse if its gravitational potential is stronger than its thermal support. (Magnetic and rotational support can also be important, but we will not consider those factors here.) A cloud in virial equilibrium with $\gamma = 5/3$ will have $E_{\rm grav} = -2E_i$, and, from our discussion of the virial theorem,

$$E_i = \int_0^{\mathcal{M}_T} \frac{1}{\gamma - 1} \frac{P}{\rho} d\mathcal{M}$$

so for collapse to occur

$$E_{\rm grav} > -3(\gamma - 1) \int_0^{\mathcal{M}_T} \frac{1}{\gamma - 1} \frac{1}{\mu m_H} kT \, d\mathcal{M} \tag{29.1.1}$$

If the gas cloud is uniform, then

$$E_{\rm grav} = -\int_0^R \frac{G\mathcal{M}(r)}{r} d\mathcal{M} = -\frac{3}{5} \frac{G\mathcal{M}^2}{R} > 3 \frac{1}{\mu m_H} kT\mathcal{M} \tag{29.1.2}$$

or

$$\mathcal{M}_J > \frac{5}{G\mu m_H} kTR \tag{29.1.3}$$

If we substitute density for radius, i.e., $\rho = \mathcal{M}/(4/3)\pi R^3$, then

$$\begin{aligned} \mathcal{M}_J &> \left(\frac{5}{G\mu m_H} kT\right)^{3/2} \left(\frac{3}{4\pi\rho}\right)^{1/2} \\ &> 10^5 \mathcal{M}_\odot \left(\frac{T}{100 \text{ K}}\right)^{3/2} \left(\frac{n}{\text{cm}^{-3}}\right)^{-1/2} \end{aligned} \tag{29.1.4}$$

This is the Jeans mass, i.e., the minimum mass necessary for a collapse. (This derivation is not perfectly correct, since it assumes that the gas immediately outside the cloud is static, which is almost certainly not the case. It also neglects magnetic support, which can be significant.) Note that for a low-density cloud that is optically thin, energy is easily radiated. In this very early phase, the collapse is roughly isothermal, which means as the density becomes larger, the Jean's mass will become smaller. This leads to fragmentation of the cloud and the production of many separate cores.

Note that if re-write (29.1.4) using the sound speed, $c_s = (\gamma P/\rho)^{1/2}$ and assume an ideal, monotonic gas with ($\gamma = 5/3$), the Jean's mass becomes

$$\mathcal{M}_J > \frac{9}{2} \frac{c_s^3}{G^{3/2}\sqrt{\pi\rho}} \tag{29.1.5}$$

Also, we can replace mass with density, to derive the Jean's length, i.e., the maximum size cloud that can collapse

$$R_J > \left(\frac{15kT}{4\pi G\mu m_H \rho}\right)^{1/2} = \frac{3}{2} c_s \left(\frac{1}{\pi G\rho}\right)^{1/2} \tag{29.1.6}$$

Another way of looking at the collapse problem is to compare the timescale for free fall collapse to the timescale for a pressure way to

propagate across the cloud and restore equilibrium. In the absense of magnetic pressure, the free-fall collapse time is simply

$$R \sim \frac{1}{2} g \tau_{\text{ff}}^2 \sim \frac{1}{2} \frac{G\mathcal{M}}{R^2} \tau_{\text{ff}}^2 \implies \tau_{\text{ff}} \sim \left(\frac{3}{2\pi G \rho} \right)^{1/2} \tag{29.1.7}$$

Meanwhile, the time it takes a pressure wave to cross the cloud is

$$\tau_P \sim \frac{R}{c_s} \sim \left(\frac{3\mathcal{M}_J}{4\pi\rho} \right)^{1/3} \Big/ c_s \tag{29.1.8}$$

So for $\tau_{\text{ff}} < \tau_p$,

$$\mathcal{M}_J > \sqrt{6}\, \frac{c_s^3}{G^{3/2}\sqrt{\pi\rho}} \tag{29.1.9}$$

Initial Collapse

As a gas cloud collapses, its increasing density causes it to become opaque in the infrared. The trapped energy heats the cloud, and changes the nature of the collapse from an "isothermal" phase to an "adiabatic phase." By the definition of an adiabat,

$$P \propto \rho^{\gamma} \implies T \propto \rho^{\gamma-1} \tag{29.2.1}$$

Substituting this into the Jeans equation (29.1.4), means that

$$\mathcal{M}_J \propto \rho^{\frac{3}{2}(\gamma-1)} \cdot \rho^{-1/2} \propto \rho^{(3\gamma-4)/2} \tag{20.2.2}$$

For $\gamma = 5/3$, $\mathcal{M}_J \propto \rho^{1/2}$; in other words, the Jeans mass no longer decreases with increasing density. Thus, the cloud is no longer unstable to fragmentation will stop.

At the center of the cloud, matter is accreted onto the protostellar core. As with other accretion, half the energy heats the star, and half is radiated away.

$$\mathcal{L}_{\text{acc}} = \frac{G\mathcal{M}\dot{\mathcal{M}}}{2R} \tag{29.2.1}$$

Since the cloud is relatively faint, the thermal timescale for the cloud is large, and the accretion timescale

$$\tau_{\text{acc}} = \frac{\mathcal{M}}{\dot{\mathcal{M}}} < \frac{G\mathcal{M}}{R\mathcal{L}} \tag{29.2.2}$$

So let's compute the average luminosity of a protostellar cloud during this phase. In general, for a spherical cloud, the gravitational potential energy is

$$E_{\text{grav}} = \frac{3}{5-n}\,\frac{G\mathcal{M}^2}{R} \tag{29.2.3}$$

where n is the polytropic index. Recall that for a uniform density sphere, $n = 0$, and the coefficient becomes the familiar value of $3/5$. (If one wants to model the cloud as a polytrope with $n = 3/2$, then the coefficient $6/7$.) If half the energy is produced during collapse of a uniform cloud, then

$$\Delta E_{\text{grav}} = \frac{1}{2} \cdot \frac{3}{5} \frac{G\mathcal{M}_J^2}{R_J} \tag{29.2.4}$$

Now let's assume this energy is emitted over one free-fall time, and is emitted as blackbody radition (with efficiency, ϵ). In that case

$$\mathcal{L} \sim \frac{\Delta E_{\text{grav}}}{t_{\text{ff}}} \sim \frac{3}{10\sqrt{2}} \frac{G^{3/2}\mathcal{M}_J^{5/2}}{R_J^{5/2}} \sim 4\pi R_J^2 \sigma T^4 \cdot \epsilon \tag{29.2.5}$$

If we replace the Jean's radius with density, then the *minimum* mass for fragmentation is

$$\mathcal{M}_J(\text{min}) \sim 0.03 \left(\frac{\mathrm{T}^{1/4}}{\epsilon^{1/2}} \right) \mathcal{M}_\odot \tag{29.2.6}$$

So, for a typical temperature of $T \sim 1000$ K, the minimum fragmentation mass is of the order of a solar mass. This is typical of star formation: although the initial gas cloud may be hundreds or thousands of solar masses, the objects that form are $\sim 1\,\mathcal{M}_\odot$. The process is very inefficient!

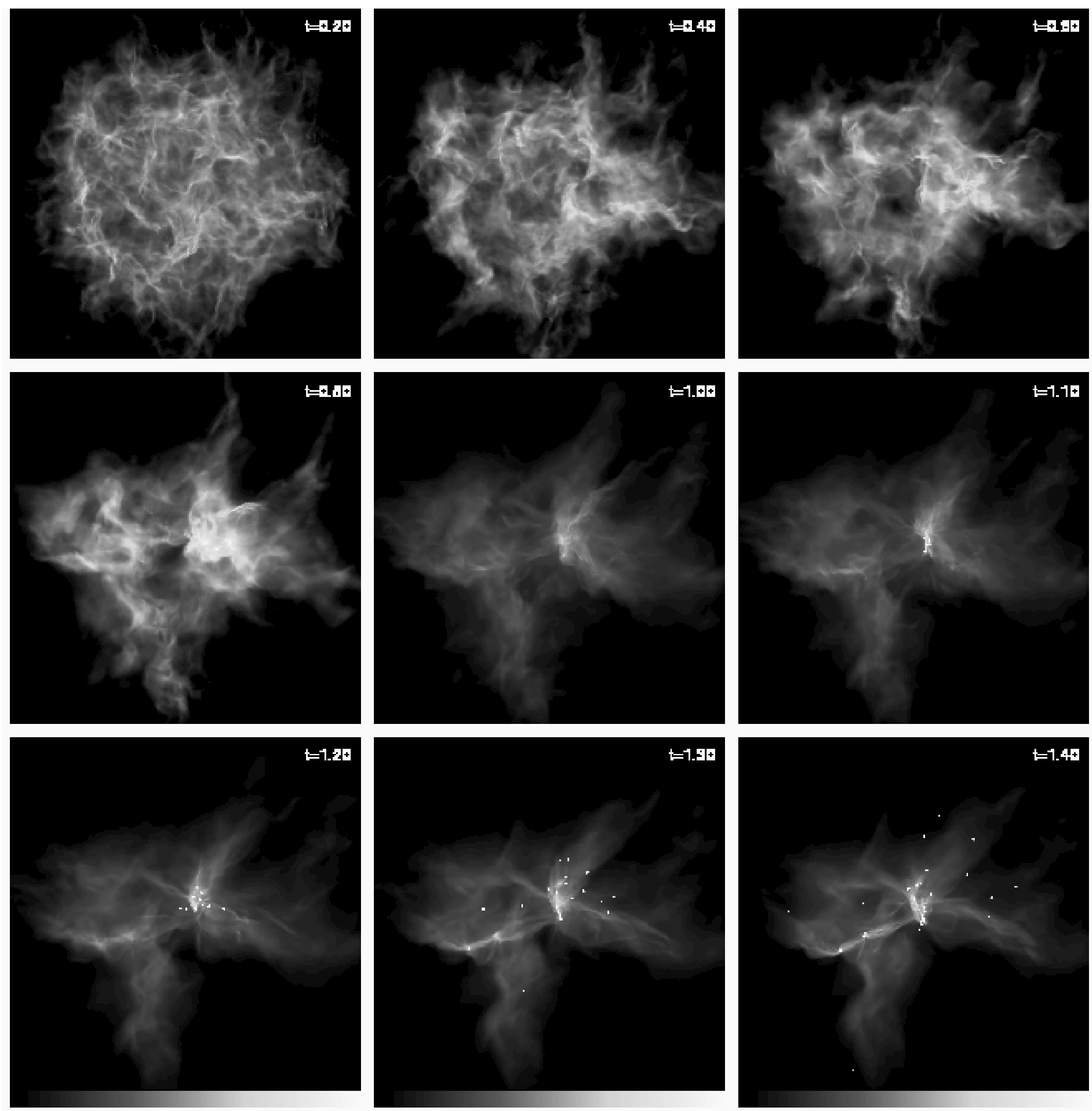
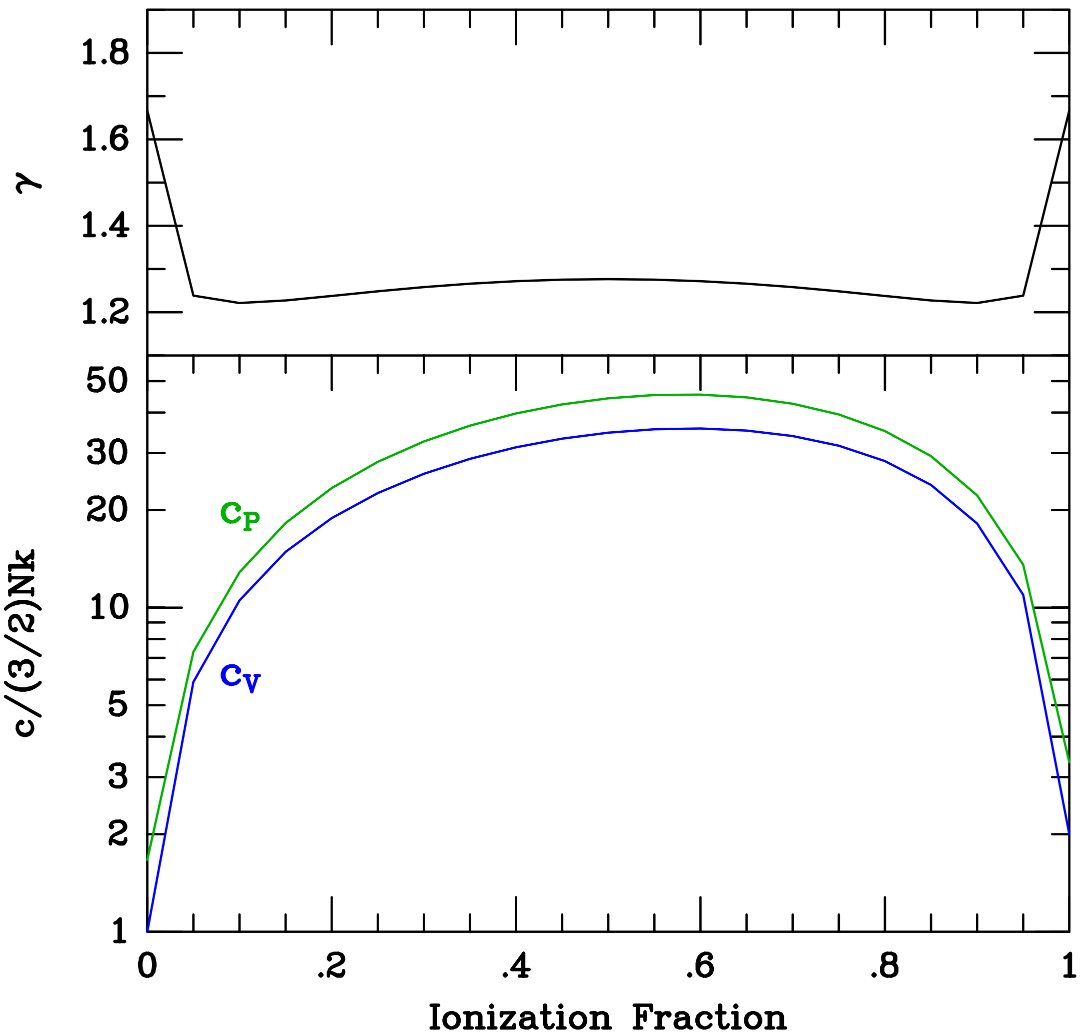


Figure 2. The global evolution of the cloud during the calculation. Shocks lead to dissipation of the turbulent energy that initially supports the cloud, allowing parts of the cloud to collapse. Star formation begins at $t = 1.04t_{\rm ff}$ in a collapsing dense core. By the end of the calculation, two more dense cores have begun forming stars (lower left of the last panel) and many of the stars and brown dwarfs have been ejected from the cloud through dynamical interactions. Each panel is 0.4 pc (82400 AU) across. Time is given in units of the initial free-fall time of 1.90×10^5 years. The panels show the logarithm of column density, N, through the cloud, with the scale covering $-1.5 < \log N < 0$ for $t < 1.0$ and $-1.7 < \log N < 1.5$ for $t \geq 1.0$ with N measured in g cm^{-2}.

Eventually, the core reaches a temperature of $\sim 2,000$ K and begins to dissociate the molecular hydrogen. At this time, the specific heats

become very large (since the energy of accretion does not raise the temperature of the gas, but just causes a change in the gas state). As a result, $\gamma = c_p/c_V < 4/3$, and, through the virial theorem (10.1.9), the star collapses quickly (on a dynamical timescale). The collapse releases energy, which further dissociates H_2. Almost immediately, all the molecular hydrogen is destroyed, and the star settles into a new hydrostatic equilibrium. The same thing happens a short time later when the temperature rises enough to ionize hydrogen (and then helium, and then helium again).



The specific heats and γ for a partially ionized plasma with a temperature of about 10,000 K. In a partially ionized plasma, energy goes into increasing the ionization, rather than raising the temperature.

Note that a substantial amount of the star's collapse in this early phase is due to these phase-change events. If the proto-star begins with a radius $R_{\rm init} \sim \infty$, then energy associated with dissociation (and ionization) is equivalent to

$$\Delta E_{\rm grav} \sim \frac{3}{10}\frac{G\mathcal{M}}{R} \sim \frac{\mathcal{M}}{m_H}\left(\frac{X}{2}\chi_{\rm H_2} + X\chi_{\rm H} + \frac{Y}{4}\chi_{\rm He} + \frac{Y}{4}\chi_{\rm He^+}\right) \tag{29.2.7}$$

where $\chi_{\rm H_2} = 4.48$ eV, $\chi_{\rm H} = 13.6$ eV, $\chi_{\rm He} = 24.6$ eV, and $\chi_{\rm He^+} = 54.4$ eV. In other words, the gravitational energy lost is equivalent to ~ 16.4 eV per baryon, and the phase change events alone are responsible for bringing a protostar from radius infinity to radius

$$R \sim 35\left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right)R_\odot \tag{29.2.8}$$

Note also that the temperature required to doubly ionize helium ($\sim 80,000$ K) is far less than that required to fuse hydrogen. In fact, throughout most of this time, the temperature is cool enough so that H^- is the dominant source of opacity. This means that the star is fully convective and on the Hayashi track.

Given that the star is on the Hayashi track (which is essentially verticle in the HR diagram), the temperature of this early-evolution proto-star is roughly 4,000 K. A size of $R \sim 35R_\odot$ then implies a luminosity of $\sim 10^3\mathcal{L}_\odot$. Note however, that *observed* pre-main sequence stars have radii substantially smaller than $35R_\odot$, indicating that additional energy must have been radiated (or otherwise lost) in the contraction process.

Hayashi Track Evolution

Fully convective stars are located on the Hayashi track. After a protostar's dynamical collapse, it will settle on the Hayashi track at a luminosity appropriate to its mass, with an radius approximately given by (29.2.8).

• Evolution will halt on the Hayashi line due to the energy injected by deuterium, which burns at $\sim 10^6$ K. This energy will up the gas pressure and keep the star from collapsing for $\sim 10^5$ yr. (Lithium burning will also temporarily halt the contraction, but for a much shorter period of time.)

• As the core heats up, more and more of the star becomes dominated by Kramers law opacity. The star will cease to become entirely convective (i.e., a radiative zone will develop). When this happens, the star will evolve blueward in the HR diagram, towards its zero age main sequence position.

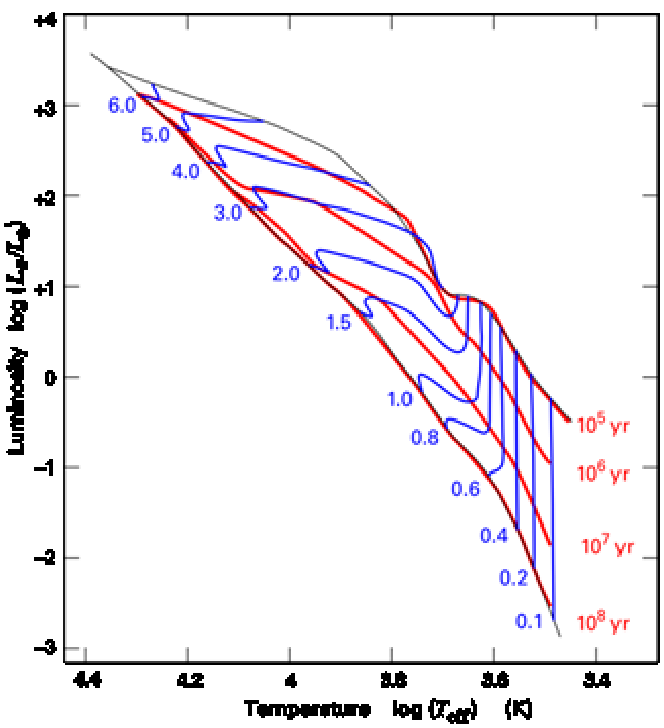
• As the star approaches the ZAMS, the first steps in CNO processing will occur (even if the core temperature isn't hot enough to support the entire cycle). Specifically, the reactions $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ and $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ will convert virtually all the core's carbon into nitrogen. (This occurs even in low mass stars which burn through the proton-proton chain.) This event causes a wiggle in the evolutionary tracks as the star approaches the ZAMS.

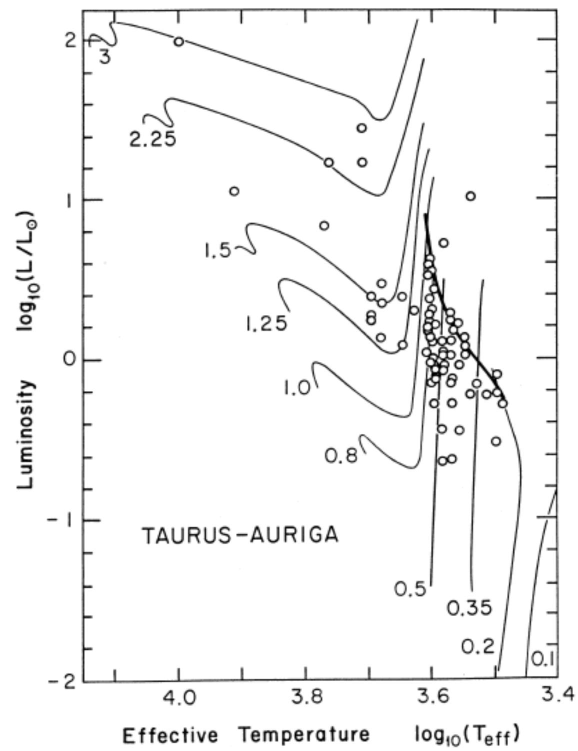
• A protostar's evolution towards the main sequence is on a Kelvin-Helmholtz timescale, i.e.,

$$\tau_{KH} \sim \frac{G\mathcal{M}^2}{R\mathcal{L}} \tag{10.2.1}$$

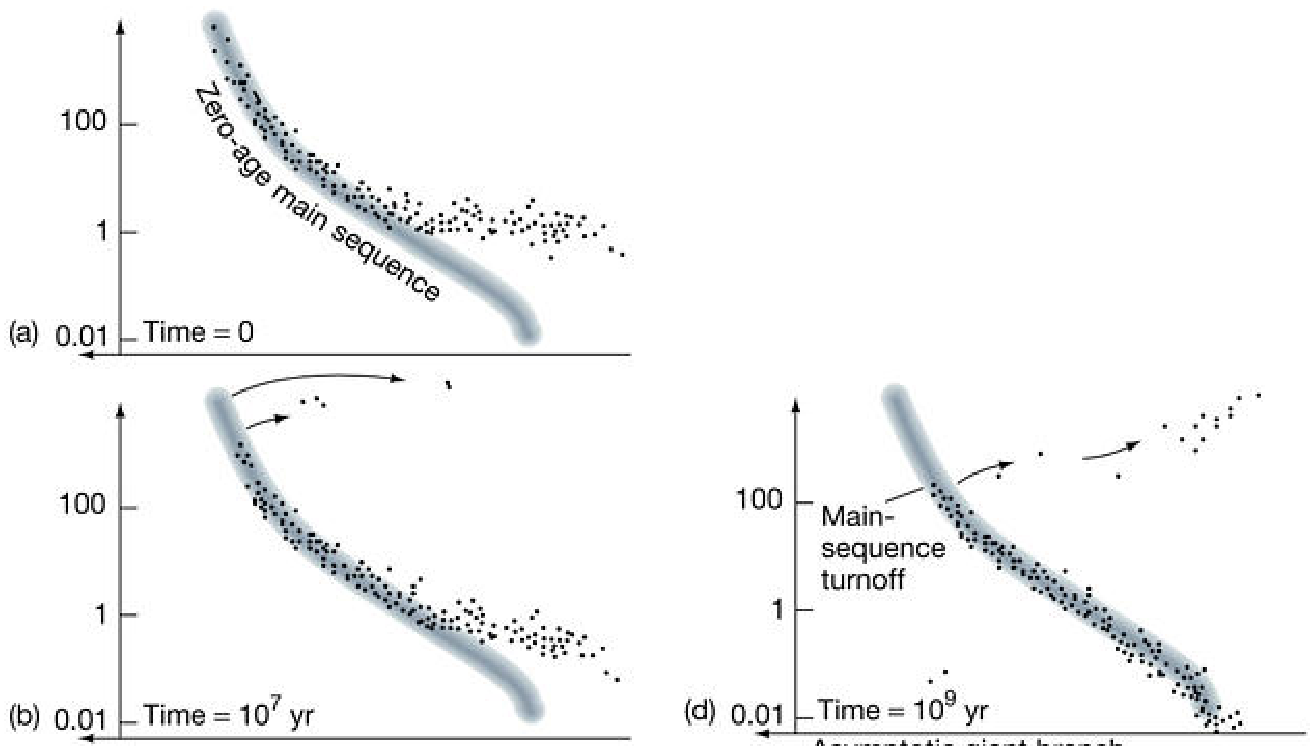
Since $\mathcal{L}$ is a high power of mass, the time it takes a star to reach the main sequence depends strongly on mass. Moreover, as the

star contracts, R gets smaller, which implies τ_{KH} gets larger. The star's pre-main sequence lifetime is therefore dominated by the final stages of contraction, when the star is already close to the ZAMS. For stars with $\mathcal{M} > 1\,\mathcal{M}_\odot$, $\tau_{KH} \sim 5 \times 10^7\,(\mathcal{M}/\mathcal{M}_\odot)^{-2.5}$ yr.





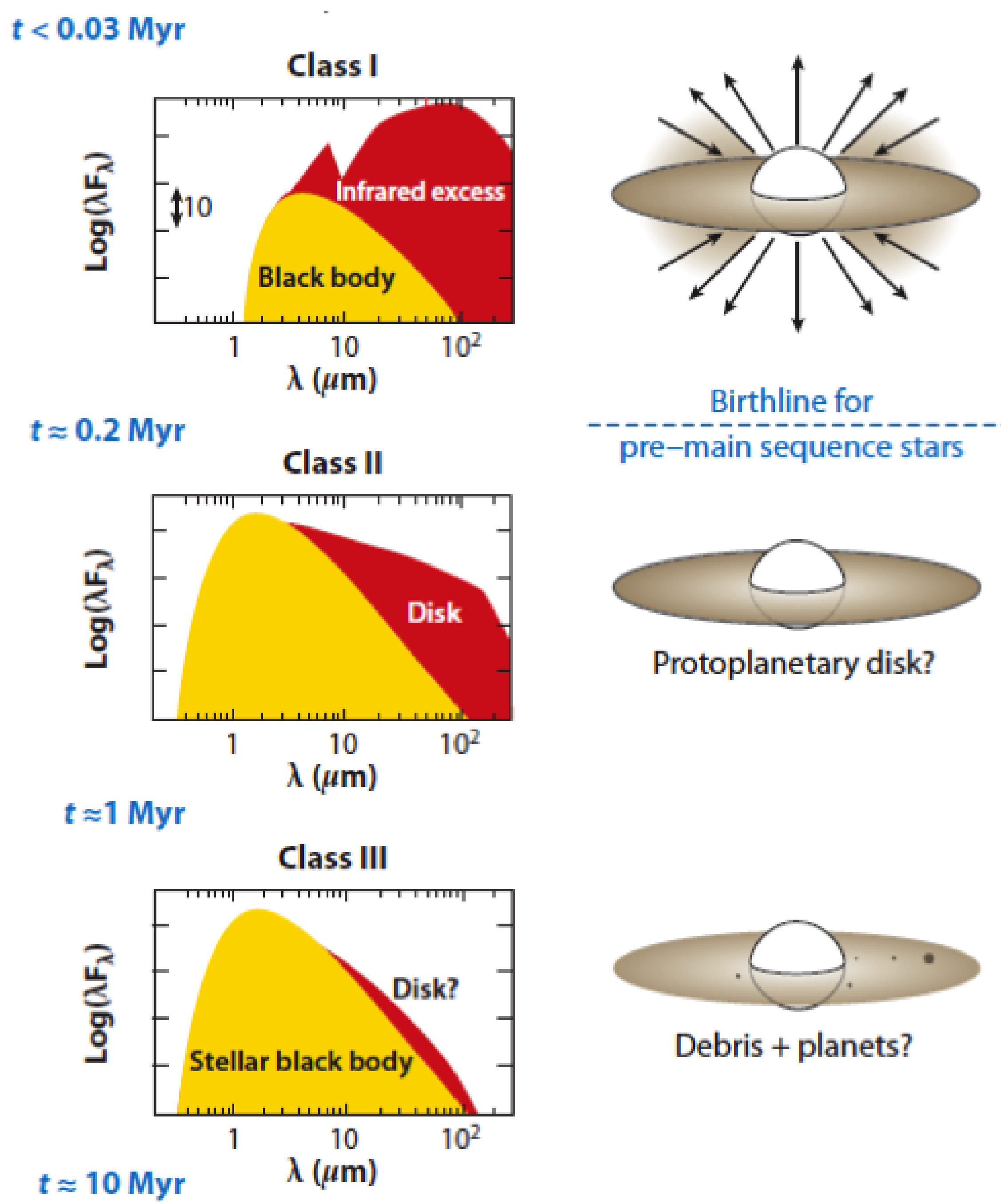
Note that the pre-main sequence timescale implies that in young star clusters, high mass stars will evolve off the main sequence before low-mass stars have finished contracting!



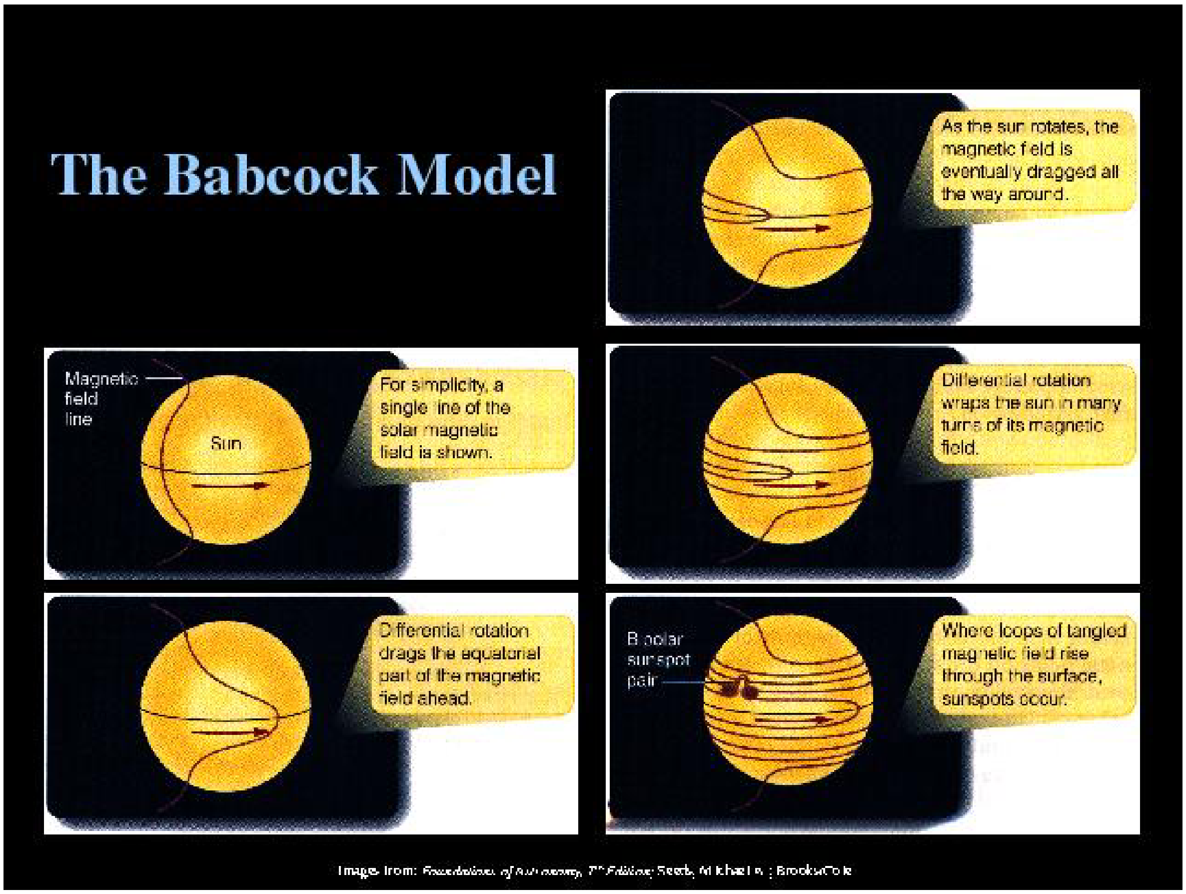
Identification of Young Stars

There are several ways to identify Young Stellar Objects:

• By infrared excess: Young stars are built up by accretion, and the accretion disk can linger for some time after the nuclear reactions have started. The dust and material in the disk can reprocess some of the light into the IR.



• By X-ray identification: Conservation of angular momentum guarantees that young stars will be rotating quickly. If the star has a convective envelope, then differential rotation will cause an increased magnetic dynamo effect, leading to increased flare activity and X-rays.



• Hα emission: The same mechanism that can create X-rays may also result in Hα emission from prominences, etc. In addition, there may still be residual Hα emission from the accretion disk.

• Lithium absorption: Lithium can be burned during the pre-main sequence phase. Moreover, in stars with convective envelopes, the temperature at the bottom of the convective layers is sufficient for lithium burning. Stars with lithium absorption in their spectrum must be young.